Design recommendations for robust thermal summer comfort in residential lightweight buildings in a moderate climate

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Abstract

The use of timber frame constructions in dwellings is gaining popularity in Belgium. Continuous improvement of EPBD requirements causes a low heating demand resulting in an increasing risk on overheating in these lightweight dwellings. Designers lack easy-to-use guidelines ensuring robust thermal summer comfort. Therefore, a parametric study with building energy simulations (BES) is conducted for a typical Flemish (Belgian) dwelling. Main design parameters and the effect of boundary conditions are analysed. The results demonstrate the critical role of effective solar protection and increased ventilation rates during occupation. The significant impact of boundary conditions shows the sensitivity of the design parameters.

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1. Introduction

Throughout the past decade the energy performance of buildings in Belgium has significantly increased, due to the continuously increasing national requirements in line with European EPBD legislation (Recast EPBD, Directive 2010/31/EU), typically resulting in improved thermal insulation and airtightness of the building envelope and application of controlled ventilation system. In combination with a steady rise in the use of timber frame construction techniques, the risk on overheating increases, especially in lightweight buildings. Consequently, measures regarding solar shading and increased ventilation have to be implemented in the design to minimize the risk of overheating, as shown in Staepels et al. [1]. However, this study also shows that traditional calculation methodologies, as used within the framework of the EPBD, prove not to be sufficient in guaranteeing thermal summer comfort in these lightweight dwellings. Therefore designers and wood construction companies request recommendations to minimize overheating risk. Weytjens et al. [2] already identified some early design default values in order to support designers of low-energy dwellings, focusing on the impact of architectural parameters on energy performance.

The objective of this study is to analyse the feasibility of putting forward quantified recommendations for the most critical design parameters, ensuring robust thermal summer comfort in lightweight dwellings. Therefore, a parametric study with building energy simulations (BES) is conducted, taking into account the complex interaction of the multitude of design parameters influencing the indoor temperature. The effect of solar shading and increased ventilation, as well as the boundary conditions, occupancy profiles and outdoor climate on thermal summer comfort is studied in a typical Flemish dwelling. The applied methodology is described in detail, followed by a discussion of the main results, resulting in conclusions and final recommendations.

This paper is the result of work package 'Thermal summer comfort" within the IWT VIS project 110803: DO-IT "Sustainable innovation of technology and comfort of wood application in the building sector" (2012-2016), aiming to establish wooden construction practices as a valuable building method within the Flemish construction sector.

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2. Methodology

For the analysis of thermal summer comfort, annual hourly building energy simulations (BES) were performed using DesignBuilder v3.0 as a user interface for EnergyPlus.

2.1. Building simulation model

The overall design of the reference building is based on a general typology as defined in KUL-BWF [3], representing a typical Flemish detached house The geometric design and orientation as well as the division into thermal zones of the ground floor are shown in Figure 1. The gross floor area and volume amount to respectively 252m^2 and 856m^3, including the garage, which is in accordance with Van Holm et al. [4]. The characteristics of the building envelope are defined according to the passive house standard,: U-values of 0.15W/m^2K for outer walls, roof and floor and 0.8W/m^2K for windows and doors. Walls are consisting of, from outside to inside: wind and water proofing layer, timber frame structure with insulation, OSB, a service cavity (5cm) and plasterboard as a finish. The total heat capacity of the building amounts to 9.2x106 J/K, which corresponds to a ‘light’ classification according to EN ISO 13790. A g-value of 0.5 was applied for the windows. The airtightness, defined as the air leakage at 50 Pa per unit envelope area, v50, is set at 0.9 m^3/m^2.h, corresponding to n50 of 0.6 h^{-1}. In combination with a window-to-floor area of 11.5%, this results in an annual net heating demand of 12.2 kWh/m^2.a.

Fig. 1. Geometric design and orientation (left) and division into thermal zones (right) of the reference building

The dwelling is divided into thermal zones (see Figure 1 right), merging adjacent rooms with similar internal heat gains and orientation for simulation purposes. In total, six thermal zones were created: (1) living room and kitchen, (2) garage, storage space, laundry room and lower hallway, (3) bedroom 1, (4) bedroom 2, (5) bedroom 3 and (6) upper hallway, bathroom and dressing.

Basic solar protection is incorporated in the building design by a window overhang on the large South oriented window in the living room (depth of 1m), and all side windows in the bedrooms (depth of 0.8m), as shown in Figure 1. The South oriented roof windows in bedrooms are equipped with automatically controlled exterior shutters to avoid overheating. The g-value of the glass is fixed at 0.5. The ventilation rates amount to 1 vol/h for zone 1 and 1.5 vol/h for zones 3, 4 and 5, and are based on Belgian standard NBN D50-001, as prescribed by national EPBD regulations. Actual ventilation rates are assumed to be 75% of the nominal rates and no heat recovery takes place during summer. Additional natural ventilation is also incorporated in the reference model, accounting for potential adaptation of the occupants during the day (7.00am until 11.00pm) by opening of windows. The multitude of parameters influencing natural ventilation rates cause rather high discrepancies in proposed values in literature, ranging from 0.5ach up to 7ach for the living room according to EN ISO 13792. From KUL-BWF et al. [3] a conservative 3ach natural ventilation rate was derived fot Flemish context, and occupants are assumed to open the windows when indoor operative temperatures exceed 24°C.

2.2. Boundary conditions

The applied internal heat gains for each individual zone of the reference model are derived from the EN ISO 13791, Annex H, including lighting, equipment and occupants and continuous presence of occupants is presumed. The radiant/convective ratio is fixed at 0.5.

Weather data is retrieved through Meteonorm for Uccle (Belgium). An average hourly weather file is generated, with hourly temperatures based on the period 2000-2009 and hourly solar radiation data from the period 1986-2005, Comparisons with measured data from the Royal Metrological Institute in Uccle for the period 2004-2008, both temperatures and solar radiation show little deviation.

Complex heat transfer between the building and the ground are not included in the building simulation, but temperatures for the ground layer were derived from the EN ISO 13370, as a function of the U-value.

2.3. Evaluation of thermal comfort

Method C as described in Annex F of the EN 15251 is selected for the evaluation of summer comfort, using a PMV-value of 0.5 as an acceptable comfort limit. While the air and mean radiant temperatures are calculated through the building simulations, a constant relative air humidity of 50% is taken into account, as well as a metabolism of 70 W/m² and an air velocity of 0.1 m/s. The clothing parameter on the other hand is defined as a function of the running mean outdoor temperature as shown in formula (1), to account for adaptation of the occupants, based on Goethals et al.[5].

$$\begin{aligned} clo &= (clo)_{min} = 0{,}5 \qquad als\ \theta_{ORMT} > 15\ ^{\circ}C \\ clo &= (clo)_{max} = 0{,}8 \qquad als\ \theta_{ORMT} < 10\ ^{\circ}C \end{aligned} \tag{1}$$

For intermediate temperatures the clo-value is linearly interpolated. The actual assessment of the indoor thermal comfort levels is based on a weighting factor, representing the actual PPD value as a function of the defined comfort limit. The product of the weighting factor and the time is then summed for a characteristic period during a year. For dwellings this period is initially set at 24 hours a day, all year, related to the assumptions regarding occupant behaviour in accordance to EN 15251. In this study, 3% annual exceedance is considered “good” thermal summer comfort, whereas an annual exceedance up to 5% is considered “acceptable”.

2.4. Parametric study

The parametric study (see Table 1) assesses the impact of solar shading, mechanical as well as additional natural ventilation and the energy performance standard. Furthermore, the impact of boundary conditions, internal heat gains and outdoor climate conditions, is studied. One variation at a time is analysed.

Regarding solar shading, both the effect of no measures limiting solar radiation (scenario n°1) as well as automatically controlled exterior solar screens, closing whenever indoor temperatures exceed 24°C, (2) placed on all windows are analysed. The impact of mechanical ventilation is studied by varying the flow rate from 50% (3) to 100% (4) of the nominal rate. Additionally, an oversized ventilation system is simulated, continuously providing 150% of the nominal ventilation rate (5) in combination with closed windows in order to assess a scenario without occupant intervention. Furthermore, the impact of the daytime increased ventilation is analysed, firstly by excluding window ventilation from the model (6). Additionally, sole night ventilation is presumed, considering a baseline temperature of 21°C and a continuous ventilation rate of 3ach (7). The effect of the energy performance of the building is analysed by changing the U-values to current minimum EPBD-requirements: 0.24W/m²K for outer walls, roofs and floors and 1.1W/m²K for glazing. The airtightness is reduced to a v50 value of 2.2 m³/m².h (8).

Table 1. Parameter variations in the parametric study

Parameter	Reference building	Scenario n°	Variation
Design parameters			
Solar shading	Overhang	1	None
		2	Solar screen g0.1 ($T_i > 24°C$)
Mechanical ventilation	75% nominal rate	3	50% nom. rate
		4	100% nom. rate
		5	150% nom. rate, windows closed
Increased ventilation	3ach ($T_{in} > 24°C$)	6	None
		7	3ach, only night time
Energy performance level	Passive house standard	8	Minimum EPBD requirements
Boundary conditions			
Internal heat gains	100%	9	50%
		10	150%
Climate conditions	Average	11	Warm
Occupancy	All day occupation	12	No daytime occupation (Mon-Fri)

Finally, a comparative analysis is conducted through assessing impact of the main boundary conditions. Firstly, varying internal heat gains were applied, ranging from 50% (9) to 150% (10). An alternative occupant scenario (11) was also simulated, both varying internal heat gains as increased ventilation rates, since the latter are assumed to be created by occupants by opening windows. Occupation is set from 6.00pm until 9.00am, assuming increased ventilation rates with high indoor temperatures during the entire interval. Finally, the effect of a warm climate (12) is studied. Therefore a 10-year extreme climate file, regarding both temperature and radiation, was generated for Uccle, using Meteonorm. Yearly averages showed to be 17,9% and 16,8% higher for, respectively, annual temperatures and radiation.

3. Results and discussion

3.1. Determining critical zone

Initial simulations showed zone 1 is by far the most critical one in the reference building, with an annual weighting factor of 393h or 4.5%, as opposed to 1.5% in zones 3 and 4, 0.6% in zone 5 and 0.2% in zone 6. These significant variations in indoor temperatures are due to the high window-to-floor ration and internal heat gains in zone 1, causing high indoor temperatures, up to 30°C, during hot summer weeks. Despite limited availability of thermal mass, daily minimum temperatures are relatively high as a consequence of low night time ventilation rates, limited to hygienic mechanical ventilation. However, with 4.5% annual exceedance of the comfort limit, the model stays within proposed acceptable comfort conditions and is used as a reference case for the parametric study.

3.2. Parametric study

The impact of design parameters and boundary conditions on the indoor comfort weighting factor is demonstrated in Figure 2. The indoor comfort level of the reference case, together with 3% (good) and 5% (acceptable) annual exceedance limitations, are also indicated. As shown in Figure 2 large variations of the indoor thermal comfort occur for the different design parameters. Annual exceedance of the thermal comfort criterion ranges from 160h or 1.8% when moveable solar screens are provided on all windows, to 3202h or 36.6% when no increased ventilation by opening the windows during the day is applied. The magnitude of the impact of solar protection is clearly shown by the results of scenario 1 and 2. In case no solar protection is provided the weighting factor increases up to 1400h exceedance or 16% of the year, whereas moveable screens on all windows results in 160h or 1.8% exceedance. Furthermore, additional research on the significance of moveable solar screens showed that control of the screens based on indoor temperature, with an operational limit of 24°C, is more effective then control based on solar radiation, in case of an operational limit of 150W/m². More in-depth analysis on the control of solar screens was beyond the scope of this study.

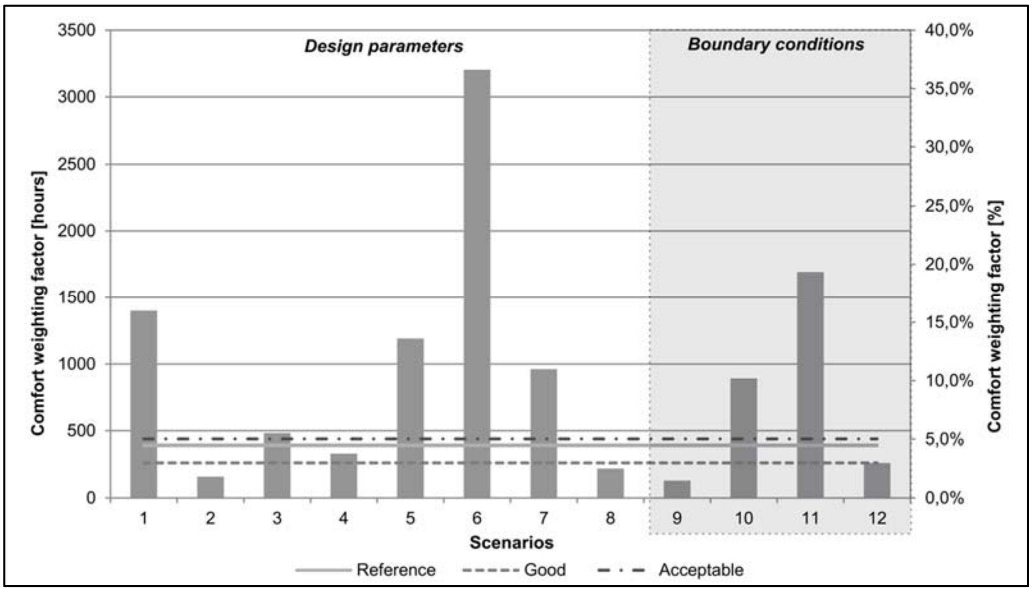

Fig. 2. Impact of parameter variations on thermal summer comfort

The small variations in ventilation rate due to altering mechanical ventilation system, cfr. scenario 3 and 4, have a limited effect on indoor comfort levels, with an increase and decrease of the weighting factor of 5.5% and 3.8% annual exceedance, respectively. Assuming no increased ventilation rates through the windows, but applying a continuous mechanical ventilation rate raised up to 150% of the nominal rate (scenario 5), corresponding to 1.5ach, the weighting factor amounts to 1190h or 13.6%.On the other hand, increased ventilation by window opening has an important impact on thermal summer comfort, given the results of ventilation scenarios 5, 6 and 7. All characterized by windows staying closed during the day, the resulting thermal comfort decreases. In case increased ventilation is completely left out of consideration (scenario 6) the annual weighting factor rises up to 3202h or 36.6%. Assuming additional natural ventilation of 3ach solely during the night time (scenario 7) results in an annual weighting factor of 960h or 11%. Due to the lightweight building model and consequent lack of thermal mass to store excessive heat, sufficient daytime ventilation rates are required to keep indoor temperatures within an acceptable range. A decreased energy performance level regarding the building envelope (scenario 8) has a significant positive effect on indoor comfort levels, with a resulting weighting factor of 221h or 2.5%. This effect is mainly a consequence of a higher U-value of the ground floor slab, which is fixed at 0.24W/m².K, allowing an increased heat flow between the rooms on the ground floor and the underlying soil, resulting in a buffering effect.

Comparatively to the impact of design parameters, Figure 2 also shows the results of the variations in boundary conditions, (scenario 9 – 12). For the applied internal heat gains interval the annual weighting factor ranged from 131h, or 1.5%, to 891h, or 10.2%. In reference to the design parameters, provision of basic solar protection and increased ventilation have a significantly larger impact on thermal comfort levels. However, the effect of the applied internal heat gains interval shows to be at least as important as applied variations in these design parameters.

Given the significant influence of internal heat gains as well as applied natural ventilation scenarios, additional analysis regarding occupancy appeared to be needed. Therefore an alternative scenario was simulated (scenario 12), without occupancy during daytime hours on weekdays. Consequently, internal heat gains are limited in these specified periods and no increased ventilation was applied. However, occupants were assumed to open windows during their presence, resulting in an annual exceedance of the weighting factor of 263h, or 3%. Analysis of indoor comfort levels under 10-year extreme warm climatic conditions show an increased discomfort up to 1691h, or 19.3% on an annual basis, thus playing an even greater role of significance in comparison to design parameters.

4. Conclusions and recommendations

This study demonstrates that ensuring good indoor comfort levels in lightweight timber frame buildings, designed according to passive house standard, is feasible. The results of the parametric study of design parameters clearly demonstrate the necessity of both adequate solar protection, with at least movable solar screens on all East, South and West oriented windows, as well as sufficient increased ventilation rates during occupation.

Since the analysis is highly sensitive towards the main design parameters in regard to the applied boundary conditions, a sensible definition of internal heat gains and outdoor climate is essential to evaluate indoor summer comfort of a dwelling. However, the large discrepancies between internal heat gains according to European standards and literature shows that prudence is called for when utilizing these values. In addition to the use of long term averaged weather data, utilisation of short term extremes could be beneficial for analysis of typical hot summer periods, providing additional insights in thermal behaviour.

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